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On some effects and the mechanism of gas dilution for high pressure turbulent premixed flames

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Introduction

Gas dilution effects :

1) Reactant diluted with products :

   EGR, FGR, HiTAC, Mild Combustion

   - NOx reduction due to flame cooling (EGR, FGR)
   - Application of HiTAC to gas-turbine combustors (HiTAC, EGR)
   - Effects on HCCI engine operation (EGR)

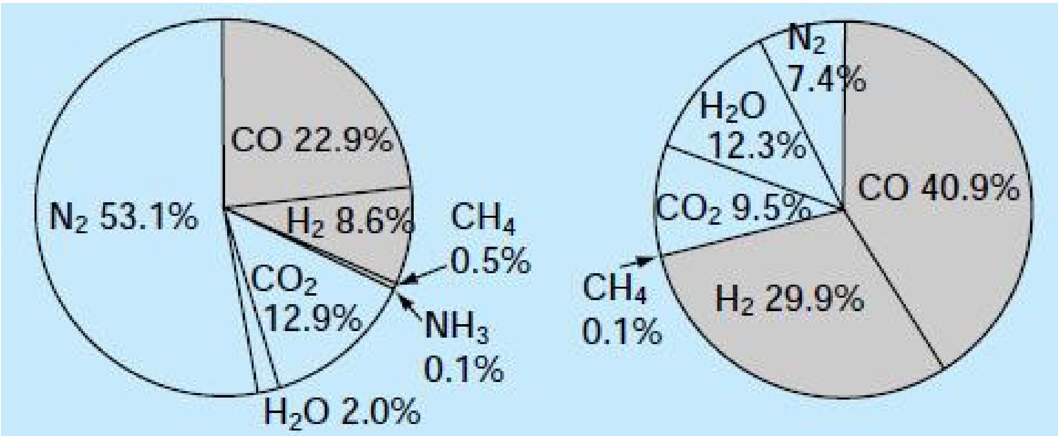
2) Reactant diluted with other fuels :

   Syngas, Hydrogen addition, Multi-component fuel, Bio-fuel

   - IGCC or natural gas reforming to H_2 including CO_2 recovery
   - Combustion enhancement (Hydrogen addition)
   - Combustion of multi-component fuel including bio-ethanol (Bio-fuel)

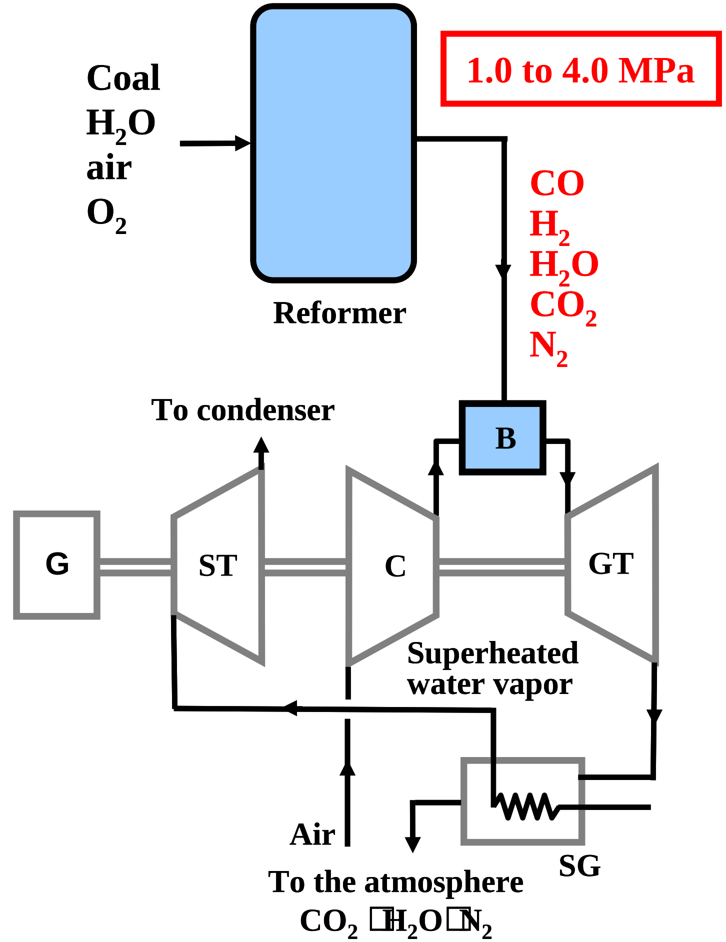
Introduction (cont.)

Composition of diluted reactant gas :



Low caloric syngas High caloric syngas

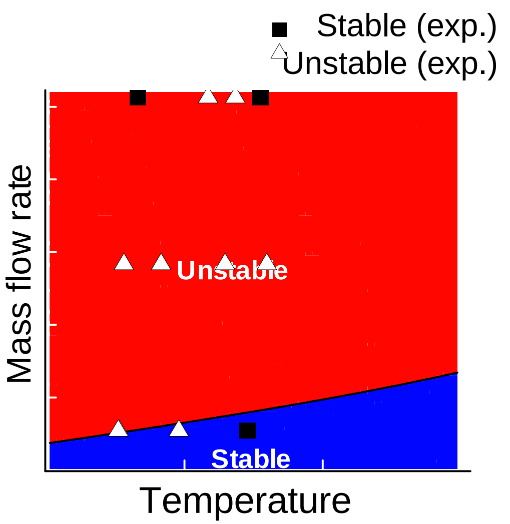
Composition of syngas reformed from coal in IGCC

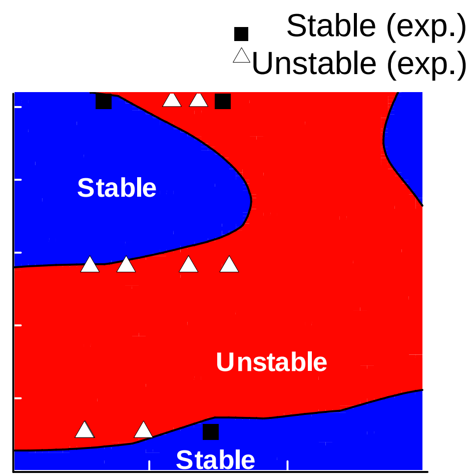


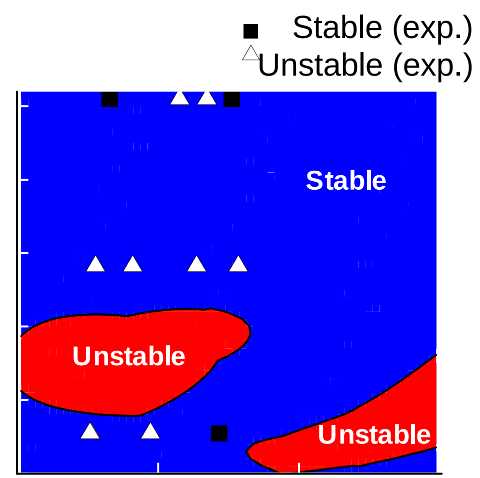
Dilution effects of CO, H_2, CO_2, H_2O, on turbulent premixed flame at high pressure and temperature should be investigated systematically.

Background (cont.)

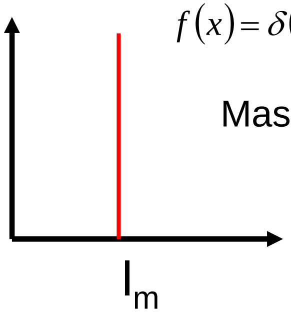
- ✓ Results of linear stability analysis showed that pressure perturbation generates fluctuation of fuel concentration, leading to combustion oscillation.
- ✓ In premixed-type gas-turbine combustors, widen heat source profile can extend the stable region in operation conditions. (Kato et al., *PCI* (2005))







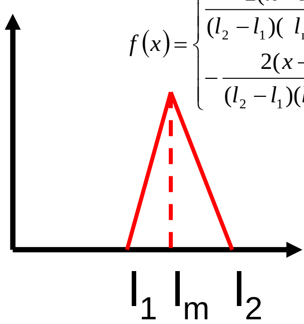
$$f(x) = \delta(x - l_m)$$



Mass flow rate

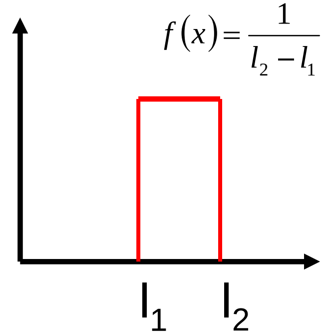
Conventional heat source model

$$f(x) = \begin{cases} \dfrac{2(x-l_1)}{(l_2-l_1)(l_m-l_1)} & l_1 \le x \le l_m \\ -\dfrac{2(x-l_2)}{(l_2-l_1)(l_2-l_m)} & l_m \le x \le l_2 \end{cases}$$



Triangular shape heat source model

$$f(x) = \frac{1}{l_2 - l_1} \qquad l_1 \le x \le l_2$$



Top-hat shape heat source model

Experimental methods and conditions

Combustion experiment

- Bunsen-type turbulent premixed flames stabilized in a high-pressure chamber at constant pressure (O.D.20 mm burner)
- CH_4/air/H_2O and CH_4/air/CO_2 mixtures with equivalence ratio of 0.9
- Mixture temperature of 573 K at 0.5 and 1.0 MPa

Dilution ratio of H_2O and CO_2

Z_{H2O} (= $[H_2O]$ / ([air] + $[H_2O]$)) and Z_{CO2} (= $[CO_2]$ / ([air] + $[CO_2]$))

Z_{H2O} and Z_{CO2}= 0, 0.05, 0.1

Turbulence measurement

- A constant-temperature hot-wire anemometer and a platinum/iridium probe.
- In non-diluted condition because of small difference in ν less than 6%

OH-PLIF

- Finest pixel resolution at the plane of measurement of 54 μm for fractal analysis
- For <c> determination, binning of four pixels; resolution of 108 μm

Gas analyzing

- Burnt gas was sampled downstream of the flame using a water-cooled sampling probe with inner diameter of 2.0 mm made of Inconel.

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Experimental setup

High-pressure chamber

Inner diameter : 500 mm

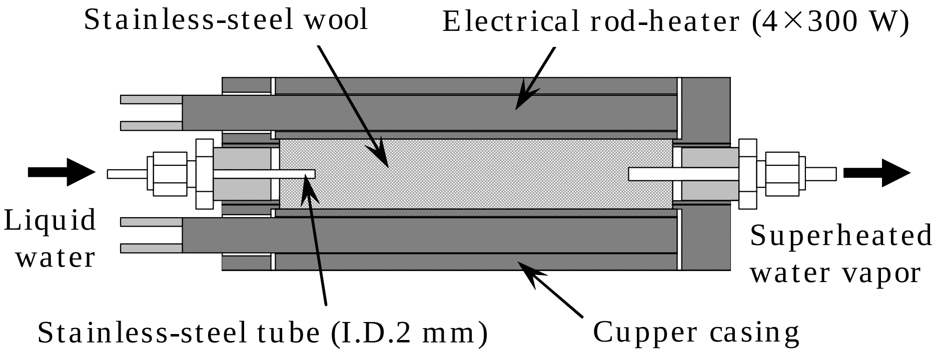
Inner height : 1100 mm

Max. pressure : 10 MPa

Electrical air-heater

Material : copper

Total power : 10 kW

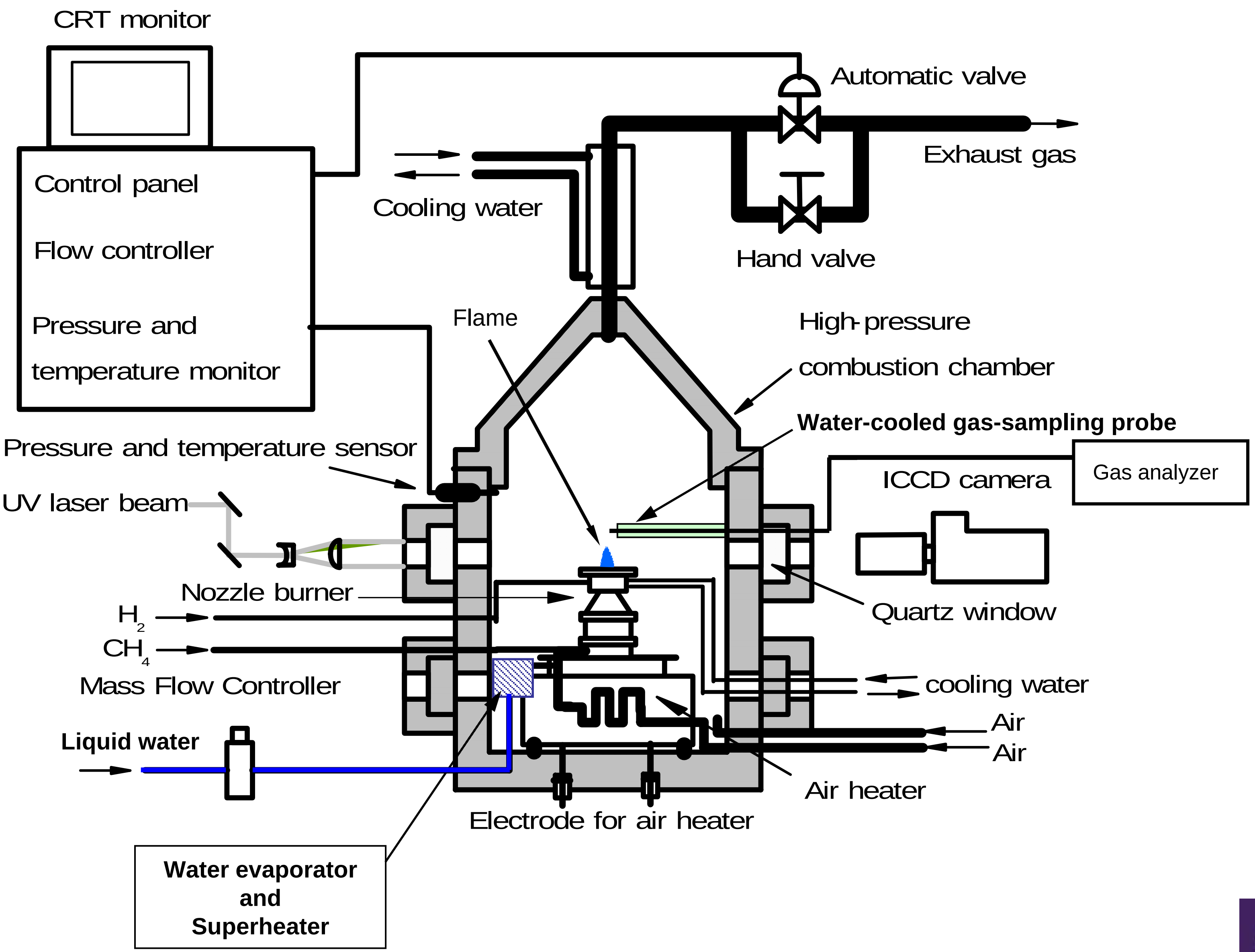


Water evaporator

Material : copper and stainless steel

Total power : 1.2 kW

Experimental setup (cont.)



Properties of mixtures in the present experiment

$\phi = 0.9$

P (MPa)	T_0 (K)	Dilution ratio Z	Moler fraction of O_2 in air	Moler fraction of CH_4 in mixture	$S_{L\,H2O}$ (cm/s)	$S_{L\,CO2}$ (cm/s)
					S_L of diluted mixtures	
0.1	573	0.00	0.192	0.086	109.20	109.20
0.1	573	0.05	0.183	0.082	93.09	81.83
0.1	573	0.10	0.174	0.078	77.35	60.79
0.5	573	0.00	0.192	0.086	59.57	59.57
0.5	573	0.05	0.183	0.082	47.86	42.58
0.5	573	0.10	0.174	0.078	37.53	30.04
1.0	573	0.00	0.192	0.086	43.44	43.44
1.0	573	0.05	0.183	0.082	34.52	30.62
1.0	573	0.10	0.174	0.078	26.87	21.29

$S_{L\,H2O}$ is about 20 % higher than $S_{L\,CO2}$

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Direct photographs

0.5 MPa, 573 K, U=5.73 m/s, u’=0.45 m/s

Diluted with superheated water vapor

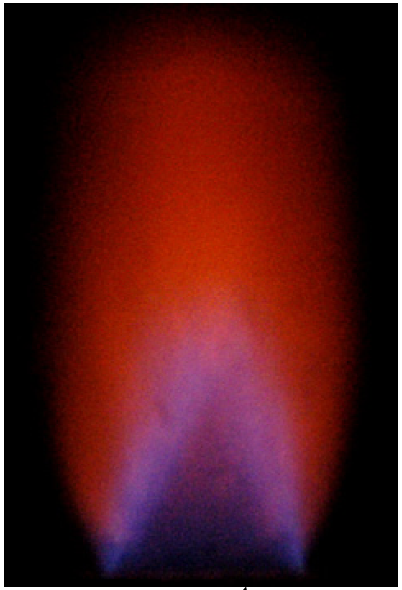
$Z_{H2O} = 0$

$Z_{H2O} = 0.05$

$Z_{H2O} = 0.1$

Diluted with wet water vapor

$Z_{H2O} = 0.1$

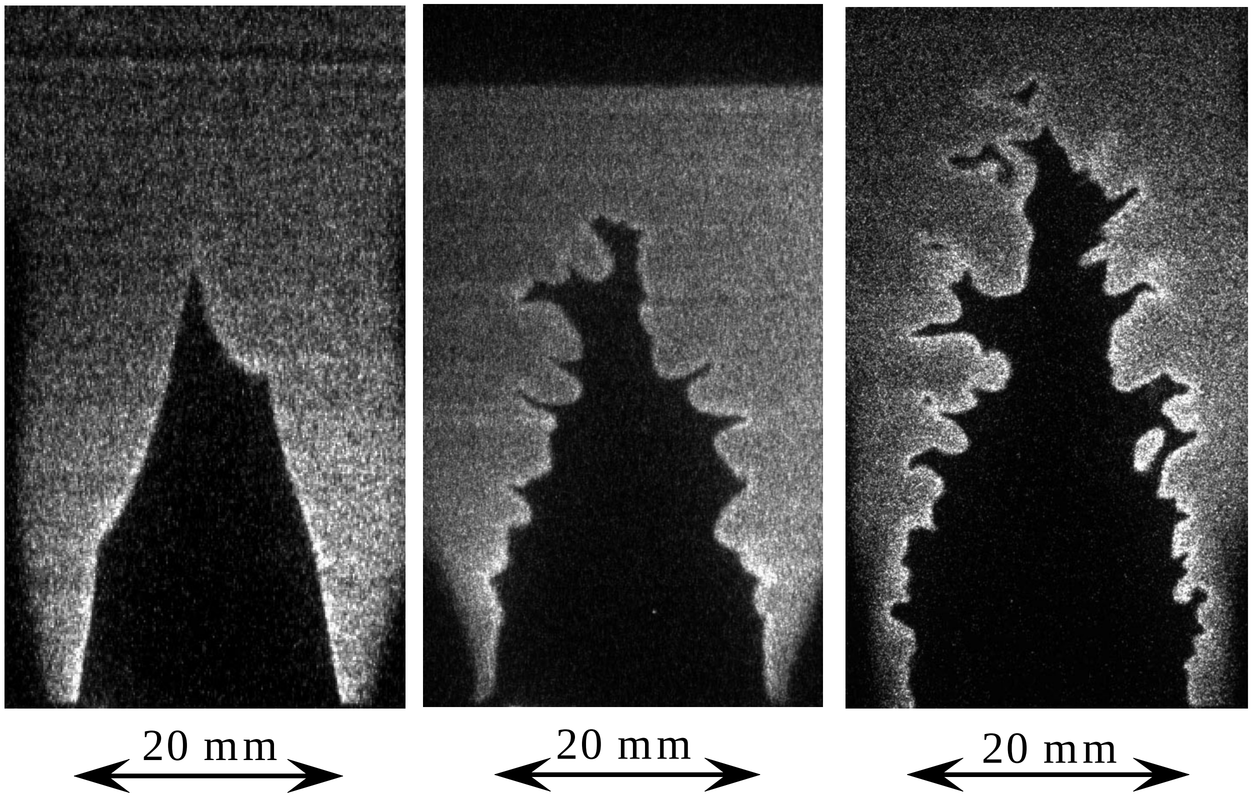


Red luminescence from H_2O visible to the naked eye and a color video camera increased extensively (650 and 720 nm band).

Red spots due to non-uniform concentration of water vapor in the flame brush was clearly seen and the flame brush became unstable.

Comparison of OH-PLIF images for H_2O and CO_2 dilutions

0.5 MPa
573 K



Z_{H2O}=0.1, $u'/S_L \cong 0$ — U=2.9 m/s

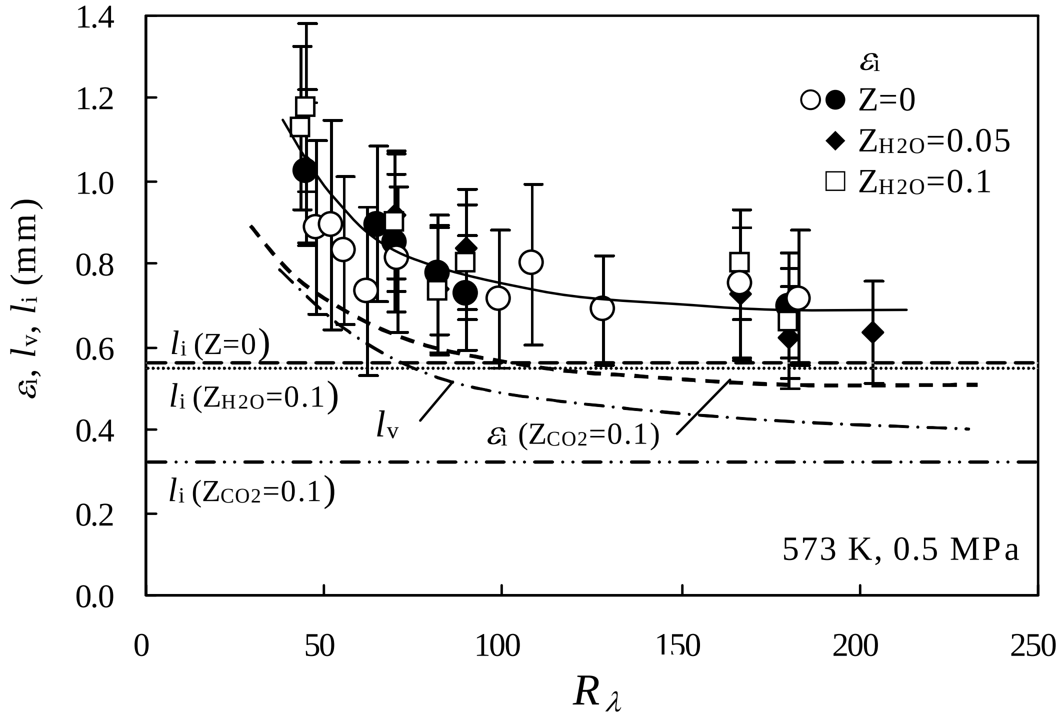
Z_{H2O}=0.1, u'/S_L=1.2 — U=5.7 m/s

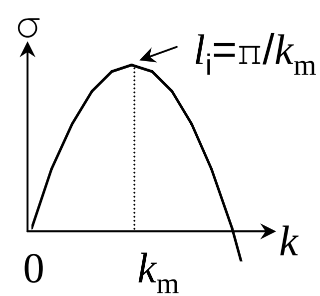
Z_{CO2}=0.1, u'/S_L=1.2 — U=3.8 m/s

Depth of wrinkling and convoluted structure for CO_2 diluted flame is more extensive compared to that of water-vapor-diluted flame.

Variations of characteristics length scales of the flame region

Scale relation is one of the indicator of the flame response against flow turbulence.
(Scale relation proposed by Kobayashi et al., *PCI* (2002))



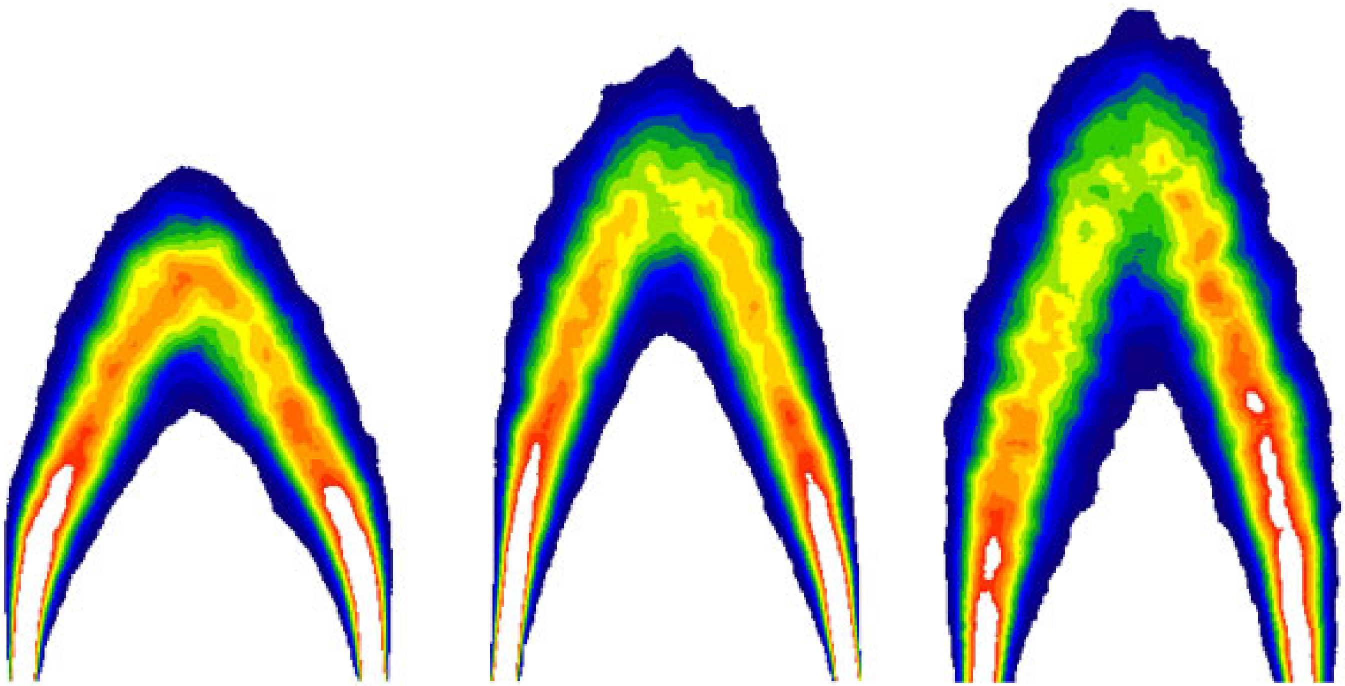


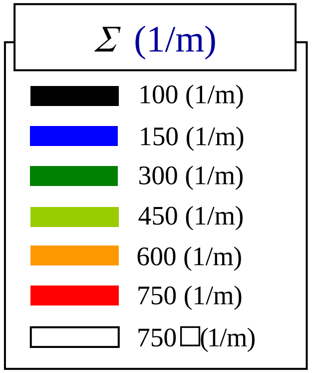
ε_i : fractal inner cutoff for high-resolution OH-PLIF images
l_i : characteristic scale of intrinsic flame instability
l_v : average scale of the vortex-tube diameter, $l_v=10\eta_\kappa$

The smallest scale of flame wrinkling in the case of water vapor dilution is almost two times larger than that in the case of CO_2 dilution, implying the flames diluted with superheated water vapor is not passive against flow turbulence.

Measurement of flame surface density Σ

0.5 MPa, 573 K, ϕ = 0.9





Z_{H2O}=0.0, u'/S_L=1.2

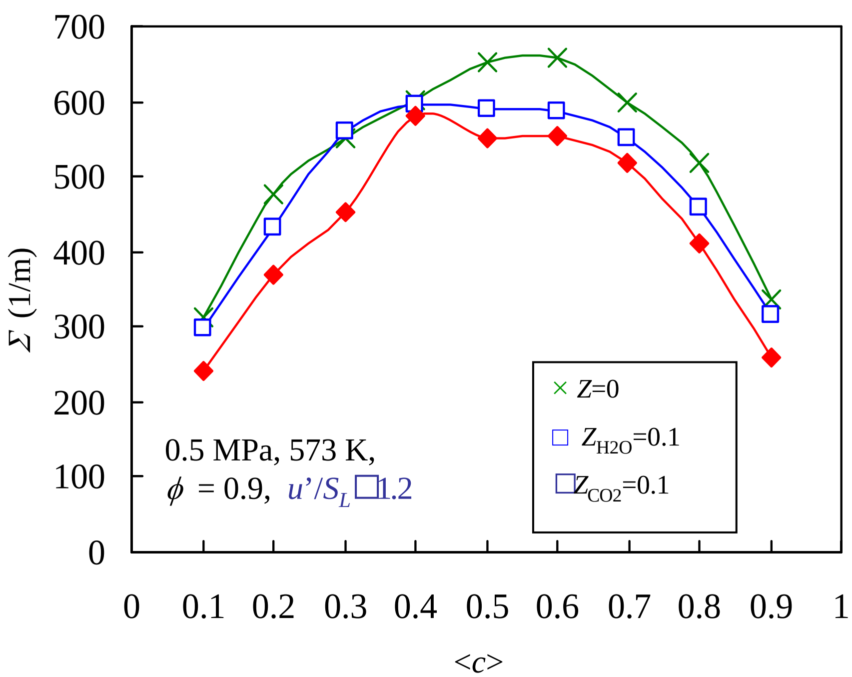
Z_{H2O}=0.1, u'/S_L=1.2
U=5.7 m/s

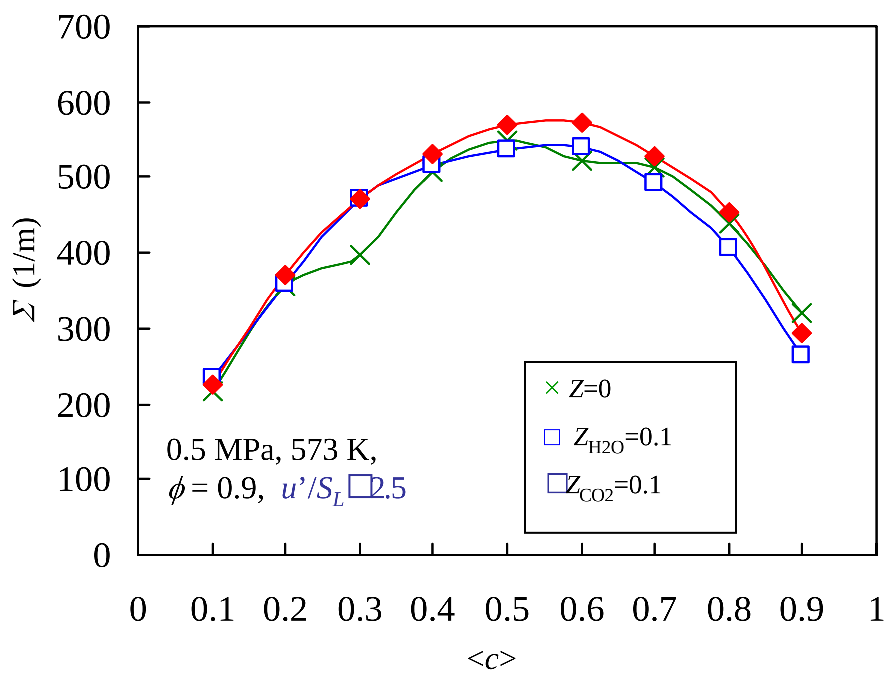
Z_{CO2}=0.1, u'/S_L=1.2
U=3.8 m/s

Profiles of Σ corresponds well to the increase in V_f shown later.

Relationship between <c> and Σ

0.5 MPa, 573 K, $\phi = 0.9$

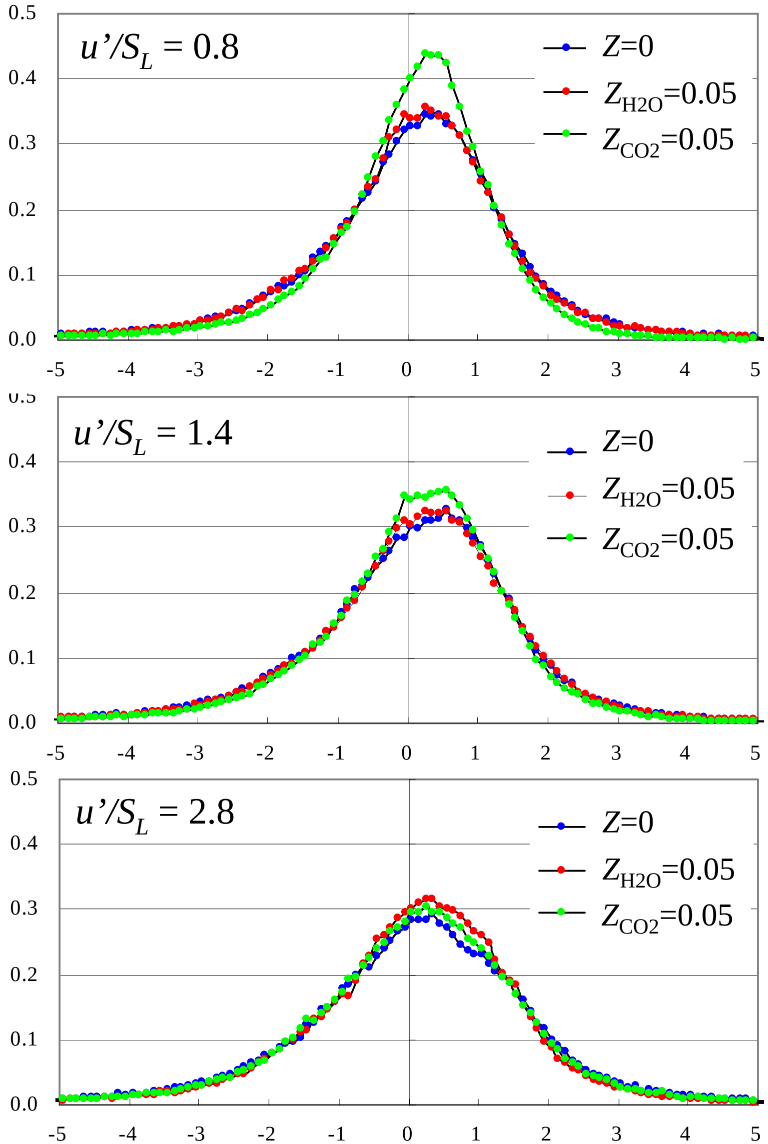




Difference in the Σ - <c> relation becomes small with increase in u'/S_L.

PDF of flame curvature

0.5 MPa, 573 K, $\phi = 0.9$



<u>Dilution effects of CO_2 and H_2O</u>

H_2O dilution :

- Change in variation is small
- Depth of wrinkle correspond to this.

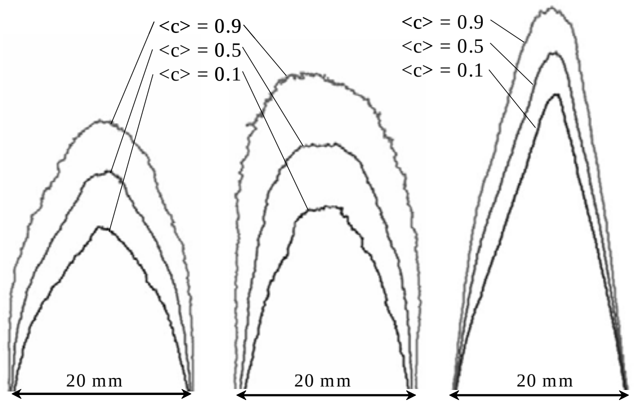
CO_2 dilution :

- Steep profiles for small u'/S_L
- The peak decreases for large u'/S_L

✓ The profiles become almost identical for large u'/S_L.

Variations of mean volume of turbulent flame region V_f

V_f has been defined by the volume of the region between <c>=0.1 and <c>=0.9.

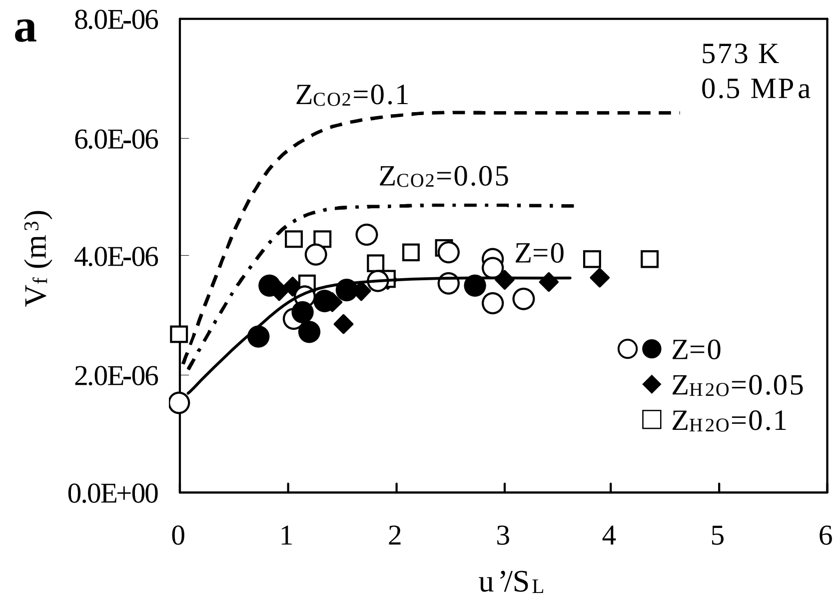


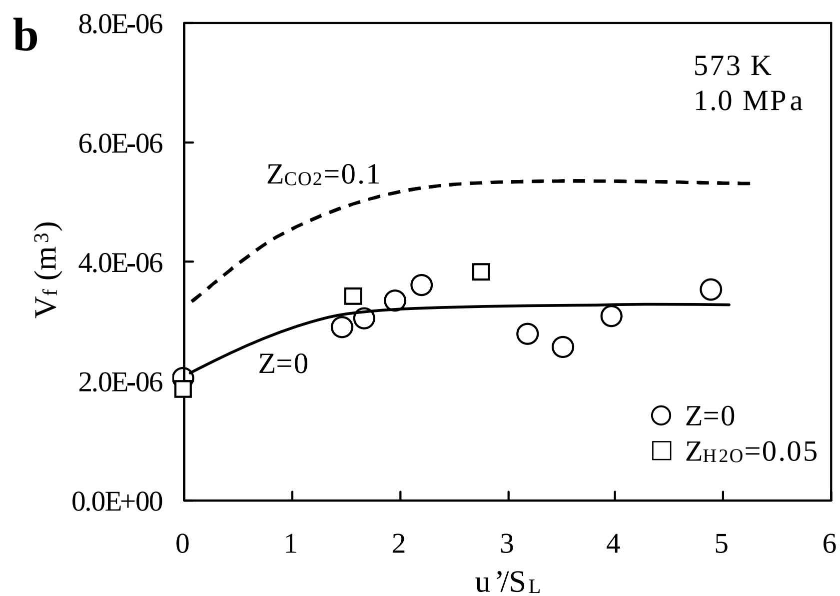
Z=0
$u'/S_L = 1.17$

Z=0.05
$u'/S_L = 3.26$

Z=0.05
$u'/S_L \cong 0$

CO_2 dilution cases
(Kobayashi et al., PCI (2007))

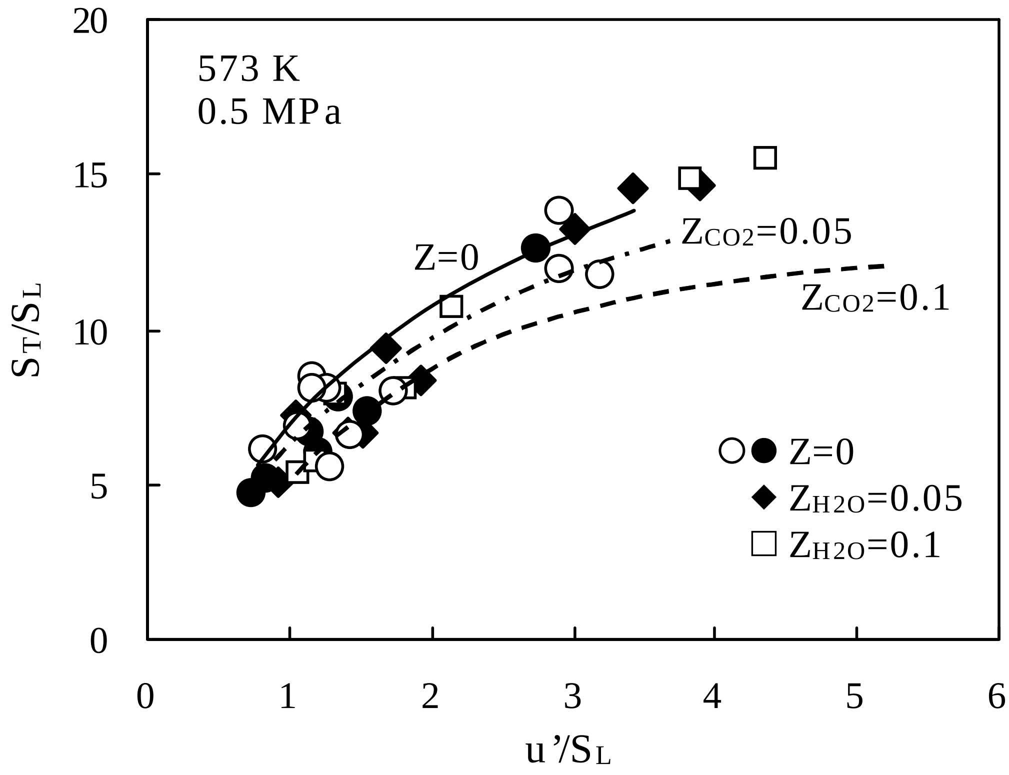




Effects of water vapor dilution on the increase in mean volume of turbulent flame region is very small compared to the cases of CO_2 dilution.

Variations of turbulent burning velocity S_T/S_L

S_T was measured by angle method for the contour of mean progress variable <c> =0.1 calculated using 500 OH-PLIF images.



S_T/S_L variations with u'/S_L are almost on the same curve for Z=0 even for Z_{H2O}=0.1, while CO_2 dilution has significant effects on S_T/S_L variations.

Dilution effects of superheated water vapor on characteristics of turbulent premixed flames at high pressure

Dilution with superheated water vapor

↓

The smallest scale of flame wrinkling is larger (from scale relation), while depth of the wrinkling is not larger compared to the CO_2 diluted case (from OH-PLIF).

↓

The mean volume of the turbulent flame region V_f, which was not affected by the dilution ratio Z_{H2O} either, is also due to the non-passive feature of water-vapor-diluted flames at high pressure.

↓

Effects of EGR at high pressure on the structure on turbulent flame region is predominated by recycled CO_2, thus only water vapor dilution is not effective for restraining the combustion oscillation of premixed-type gas-turbine combustors in terms of widening of the heat release region.

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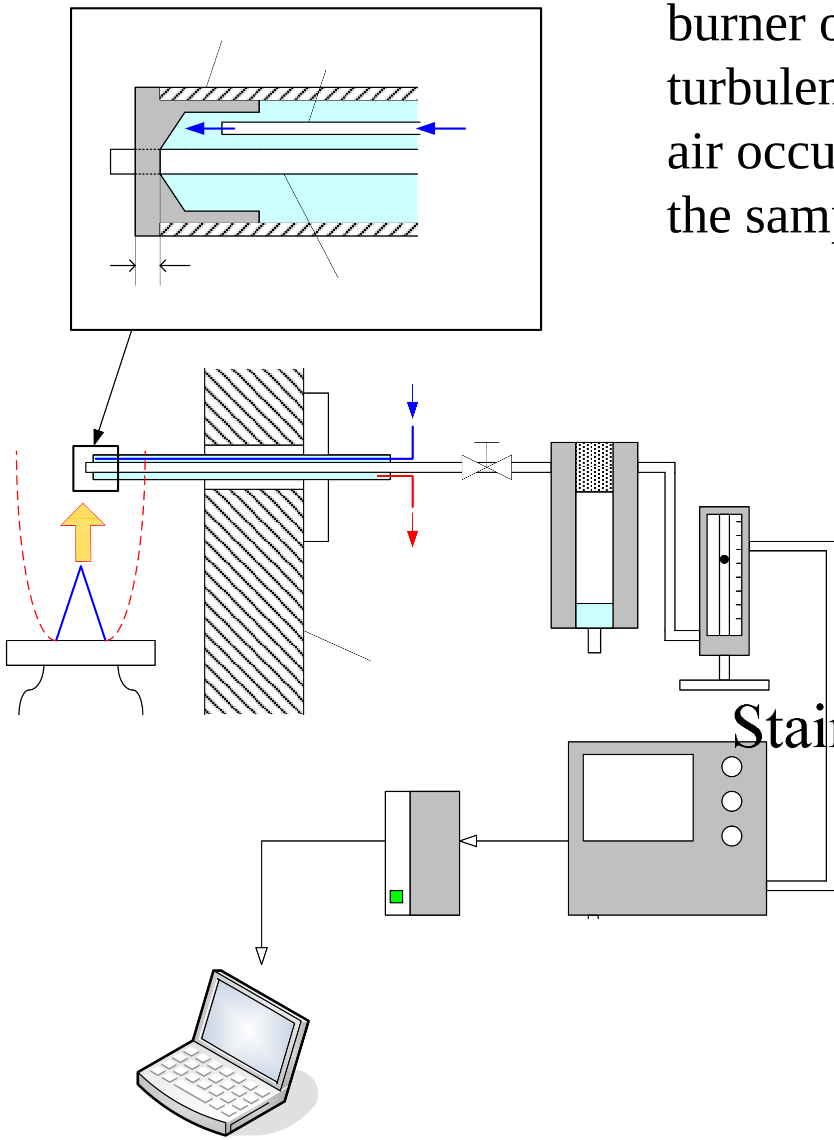
CO and NOx measurement in burnt gas region

The gas was sampled 75 mm downstream of the burner outlet on the central burner axis for non-turbulent flame where no mixing with surrounding air occurs. It was confirmed from OH-PLIF that the sampling point is in the burnt gas flow.



Emission Index (EINOx, EICO) $= \dfrac{Y_{\text{product out}}}{Y_{\text{fuel in}}}$

$Y_{\text{product out}}$: CO and NOx mass fraction in burnt gas flow

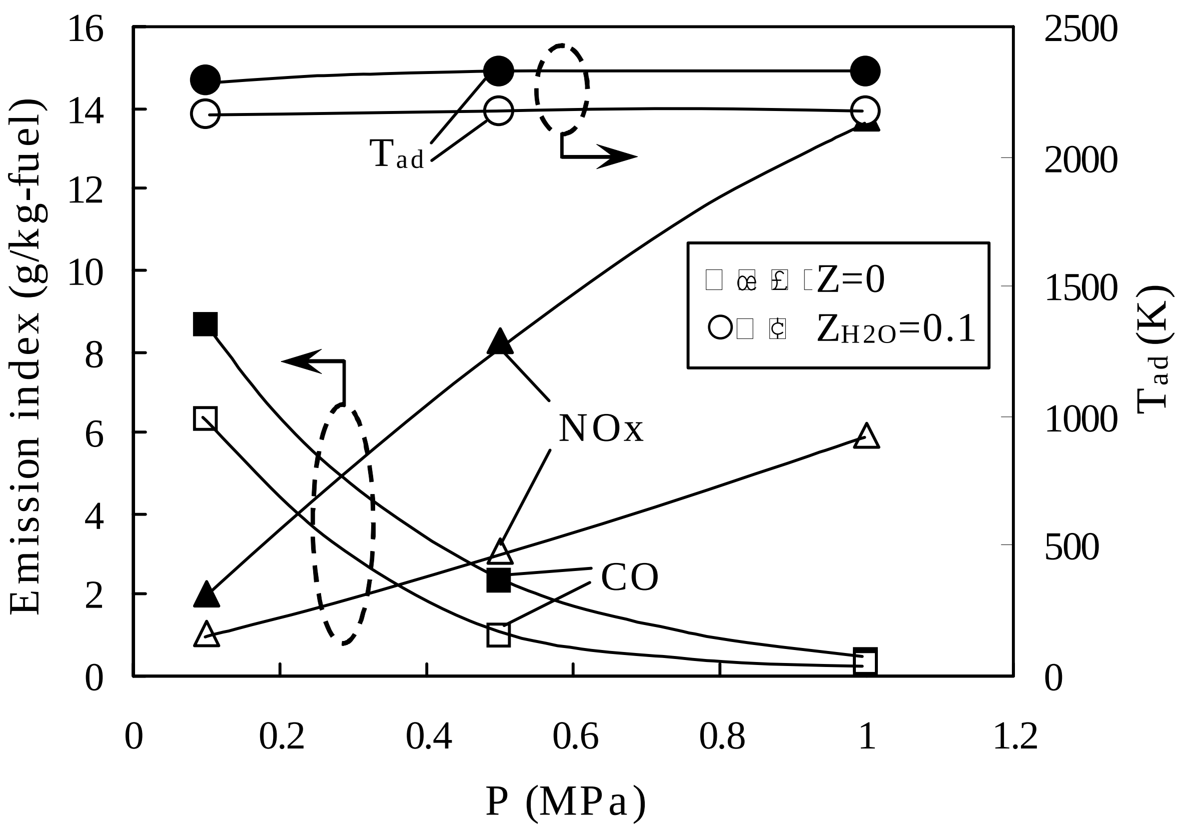
$Y_{\text{fuel in}}$: CH_4 mass fraction in unburnt gas

Stainless steel tube (ID=1

CO and NOx mass fractions were calculated considering removed H_2O before the gas analyzing

Wat

Variations of adiabatic flame temperature and measured emission indices of CO and NOx with pressure

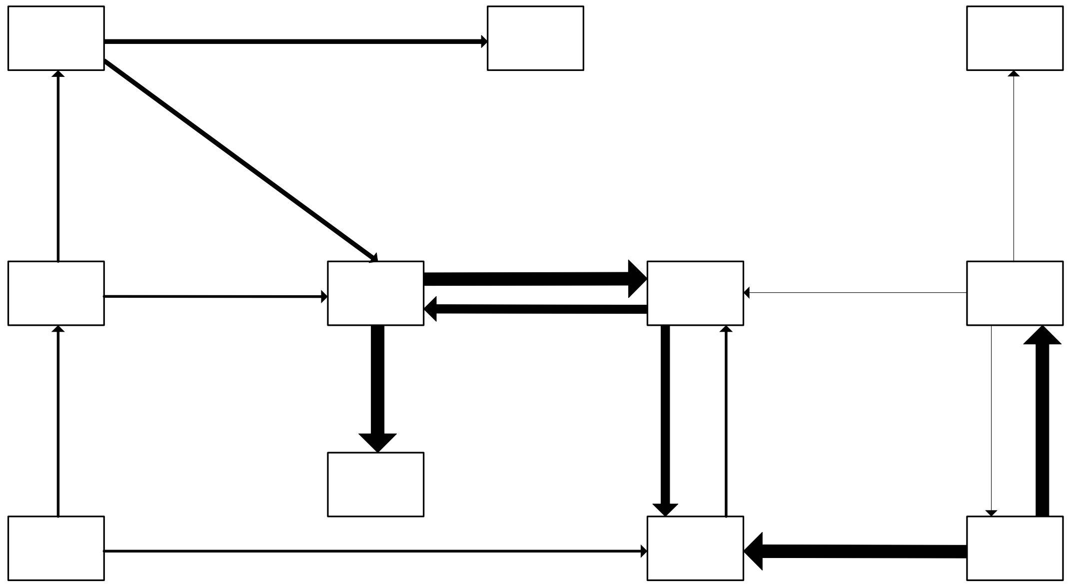


- ✓ EINOx increase with pressure, while the increase becomes weak for the mixture diluted with superheated water vapor.
- ✓ EICO decreases with pressure and also the effect of water vapor dilution is clearly seen, indicating suitable condition in terms of application of HiTAC to high-load combustor.

Mechanism of CO reduction by H_2O dilution at high pressure

From sensitivity analysis of the peak CO production rate for 1-D premixed flame

R1 : $OH + CO = H + CO_2$
R2 : $H + O_2 = O + OH$
R3 : $H + CH_3\ (+M) = CH_4\ (+M)$
R4 : $OH + H_2 = H + H_2O$
R5 : $2OH = H_2O + O$
R6 : $OH + CH_4 = CH_3 + H_2O$
R7 : $OH + CH_2O = HCO + H_2O$
R8 : $HO_2 + CH_3 = OH + CH_3O$
R9 : $HCO + H_2O = H + CO + H_2O$



1.0 MPa
573 K,
$Z_{H2O}=0.1$

Higher concentration of H_2O produces OH radical rapidly and the elementary reaction $CO+OH=CO_2+H$, which composes the water-gas-shift reaction ($CO+H_2O=CO_2+H_2$), is enhanced and thus CO emission is reduced.

Summary

- Effects of H_2O dilution on S_T/S_L and the mean volume of turbulent flame region, V_f , with u'/S_L in the cases of superheated-water-vapor dilution up to Z_{H2O}=0.1 at 0.5 MPa and 1.0 MPa are very small, indicating that effects of EGR at high pressure on the structure on turbulent flame region is predominated by recycled CO_2.

- When HiTAC is applied to high-load combustors, the dilution of burned gas with superheated water vapor is effective not only for reducing NOx emission but also for reducing CO emission. The latter is presumed to be due to enhanced $CO+OH=CO_2+H$, which composes the water-gas-shift reaction ($CO+H_2O=CO_2+H_2$), and it is a preferable characteristic in terms of overcoming the possible defect of HiTAC, especially in high-load combustors operated at high pressure.

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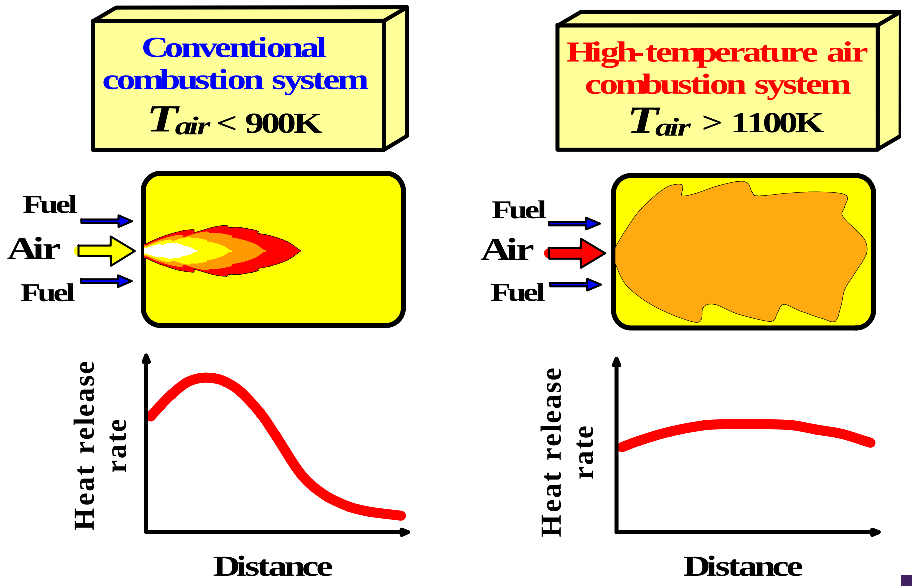
Background (cont.)

High-Temperature Air Combustion Technology (HiCOT or HiTAC) uses highly-preheated air (over 1100 K) produced by a flue-gas heat regenerator and combustion in an oxidizer with low oxygen concentration (minimum is about 4 % in volume).

Low oxygen concentration is realized by supplying burnt gas to the air inlet or by strong recirculation of the burnt gas in furnaces keeping the overall excess air ratio close to unity.

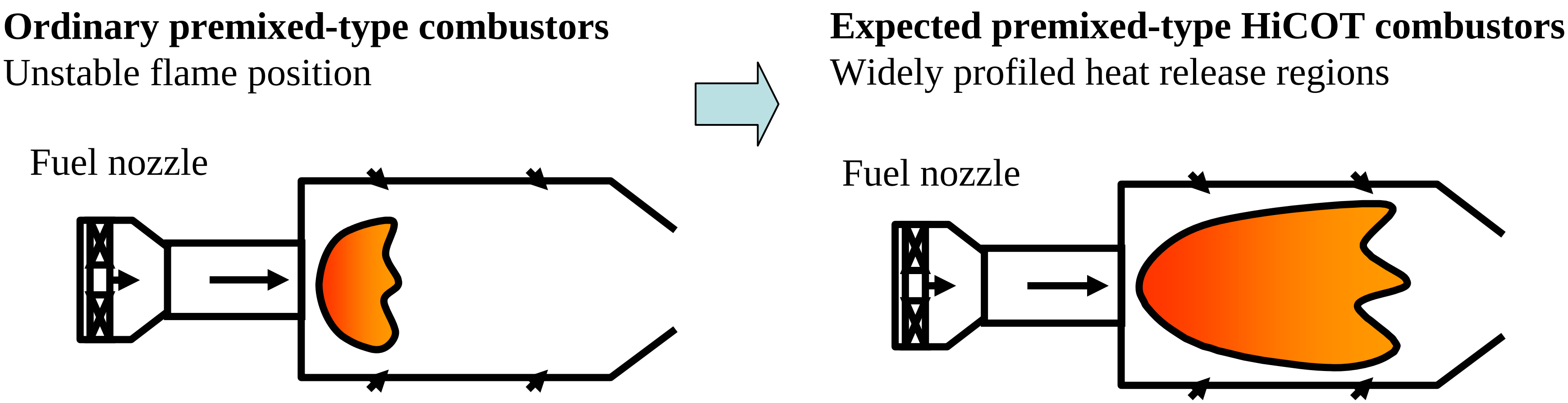
Advantages:

- High energy saving
- Reduction of NOx emission
- Low combustion noise
- Uniform heat release region and temperature profile in furnace
- Small furnace designing



Background (cont.)

In the case of EGR (FGR), a flame is formed under conditions of not only low oxygen concentration but also at high pressure and high temperature because the mixture is compressed before combustion.



If turbulent flame characteristics under HiTAC conditions are realized at high pressure, while the temperature range of gas-turbine combustors is lower than ordinary HiTAC condition, the stable operation of premixed-type gas-turbine combustors is expected.